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Consequences of future data center deployment in Canada on electricity generation and environmental impacts: a 2015–2030 prospective study

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Summary:

The environmental impacts of data centers that provide Information and Communication Technologies (ICT) services are strongly related to electricity generation. With the increasing use of ICT, many data centers are expected to be built causing more absolute impacts on the environment. As electricity distribution networks are very complex and dynamic systems, an environmental evaluation of future data centers is uncertain. This study proposes a new approach to investigate the consequences of future data center deployment in Canada and optimize this deployment based on the Energy 2020 techno-economic model in combination with life cycle assessment methodology (LCA). The method determines specific electricity sources that will power the future Canadian data centers and computes related environmental impacts based on several indicators. In case study scenarios, the largest deployment of data centers leads to the smallest impact per MW of data centers for all of the environmental indicators. It is found that an

increase in power demand by data centers would lead to a reduction in electricity exports to the US, driving the US to generate more electricity to meet its energy demand. Since electricity generation in the US is more polluting than in Canada, the deployment of data centers in Canada is indirectly linked to an increase in overall environmental impacts. However, while an optimal solution should be found to mitigate global GHG emissions, it is not clear whether the environmental burden related to US electricity generation should be attributed to the Canadian data centers.

Introduction

Information and communication technologies (ICT) are increasingly used and becoming ubiquitous in social infrastructures (DNV 2014). While providing useful services, ICT are also responsible for a growing share of global electricity consumption (over 4% of the world's electricity consumption in 2012 (Van Heddeghem et al. 2014) and the subsequent impacts on the environment, including climate change. ICT was estimated to contribute around 2% of anthropogenic greenhouse gas (GHG) emissions in 2011 (Global e-Sustainability Initiative and The Boston Consuting Group 2012). Among the ICT infrastructures and equipment, data centers represent roughly one-third of the total ICT electricity consumption (Van Heddeghem et al. 2014). Unlike end-user devices and transmission networks, which are spatially widely spread, data centers have a very localized power demand and are very energy-intensive. The environmental impacts of electricity generation depend on the type of power generation technology and each region uses a different combination of technologies to generate electricity. Thus, the environmental impacts per kilowatt-hour (kWh) differ from one region to the next (Laurent and Espinosa 2015). Since electricity consumption is an important source of environmental impacts in the life cycle of a data center (Arushanyan et al. 2014), its environmental footprint is highly correlated to its geographic location. Therefore, to properly evaluate the environmental footprint of data centers, it is critically important to identify the sources of electricity that power them. While it may be simple (when data are available) to model the technology mix generating electricity in a specific region at the present time (Maurice 2015; Dandres et al. 2014b), it is more challenging to predict the real future electricity production. Indeed, electric networks are in constant evolution to face future power demands. New power plants are regularly added to the electric grid while old ones are decommissioned. Moreover, electric networks are interconnected, and interconnection capacities may also change over time depending on import and export needs. Also, with the threat of climate change, renewable energy sources are increasingly being integrated into electric grids. Consequently, environmental impacts per kWh of electricity consumed in a region are expected to change significantly in the future. Finally, since data centers are very energy intensive and their global power demand keeps growing, they may have an impact on the future evolution of electric grids. This article therefore presents a methodology to evaluate environmental impacts related to long-term changes in regional power demand. This innovative methodology is based on the sequential use of a techno-economic model of the North American energy sector with life cycle assessment (LCA) methodology. This methodology is illustrated in a case study that addresses the environmental impacts of future data centers deployed in Canada and supplied by the electric grid. In this case study, the methodology is used to investigate and optimize the future deployment of data centers in Canada by minimizing environmental impacts related to electricity generation in Canada and the United States of America (US).

Presentation of the case study

Canada is an attractive region for data centers: the price of electricity is lower than in many other countries (Shrinkthatfootprint 2014), around two third of electricity is generated from renewable energy (International Energy Agency 2015) and available cold air may be used for free cooling (The Green Grid 2012). The last two arguments have become more important in the recent year due to the increasing environmental pressure on data centers. Therefore, it can be anticipated an acceleration of data center installation in Canada in the coming years. The change is already perceptible, as Ericsson (McNevin 2013), OVH (Miller 2014), Microsoft (Sverdlik 2015) and Amazon (Barr 2016) all recently announced their plans to implement large data centers in Canada. However, this new trend is not necessarily represented in business as usual scenarios of energy demand. Thus, this case study assess the environmental impacts of electricity generation in the context of an accelerating power demand by Canadian data centers in the 2015–2030 period. In Canada, the electricity consumed by data centers represents approximately 1% of the national electricity consumption (Natural Resources Canada 2016; DCD intelligence 2013). This case study explores situations in which the Canadian data centers' demand would reach up to 2% of the national electricity demand by 2030 instead of remaining around 1%. It is anticipated that the consequences on the electric grid of deploying additional data centers are not linear. Therefore, several prospective data center deployment scenarios were studied. These five scenarios assume different future power demands of additional data centers: from 30 to 750 MW in 2030, as presented in figure 1.

<Figure 1>

Figure 1: Scenarios of future power demands of additional data centers

These scenarios were developed in the context of a business as usual (BAU) scenario representing the global evolution of the Canadian energy demand by 2030. The BAU scenario was initially developed by the Canadian government (Environment Canada 2013) and considers an increase in the power demand of the "Information and cultural industries" (that includes Canadian data centers (Statistics Canada 2007)) of 19% (from 8.0 TWh to 9.5 TWh) over 2015–2030 with an increase in national demand of 29% in the same period. The five scenarios assume more significant data center power demand growths resulting in a greater increase in the "Information and cultural industries" demand: 22%, 24%, 30%, 40% and 75% over 2015–2030. Other aspects of the BAU scenario are presented in the Energy 2020 section. The resulting electric grid mix of each scenario was modeled using a techno-economic model, as presented in the methodology.

It is assumed that the data centers are built in the Canadian provinces with the greatest gross domestic product, population and electric power generation: Ontario, Québec and Alberta (Statistics Canada 2013). Considering that Ontario's gross domestic product is roughly twice as high as those for Quebec and Alberta (which are quite similar), it was assumed that 50% of the data centers are built in Ontario, 25% in Québec and 25% in Alberta. These provinces have very different electric grid mixes: Ontario uses mainly nuclear power, hydroelectricity and natural gas; Québec uses almost exclusively hydroelectricity and Alberta mostly generates electricity from coal and natural gas (Statistics Canada 2014). In terms of the overall electricity consumed per data center, it was considered that the data centers operate constantly at 66% of their capacity, like the high-end servers in Koomey (2007).

Method

This study combines LCA methodology with the use of the Energy 2020 techno-economic model.

LCA

LCA is a method designed to study the environmental impacts of products and services based on their life cycles. The methodology is defined in ISO standards (ISO 14040-14044) and remains under development since new products and new situations create new methodological needs. It is possible to distinguish between attributional and consequential LCA approaches, which have different objectives. The attributional LCA objective is to evaluate the environmental impacts of a product or service over its entire life cycle at a given time (Rebitzer et al. 2004). The consequential LCA (C-LCA) objective is to analyze the environmental impacts resulting from a change in the life cycle of a product or service (Ekvall and Weidema 2004; Weidema 2003; Weidema et al. 1999). In this study, the C-LCA approach was followed.

Goal and scope

The objective of this C-LCA is to model the environmental impacts of the use phase of new Canadian data centers built in the future. It was therefore necessary to identify the marginal sources of electricity, which may be defined as the sources of electricity that are exclusively affected by the additional Canadian data centers. Concretely, the marginal electricity is identified by the techno-economic model (see Energy 2020 section).

The studied system is the entire North American energy sector because Canada is a net exporter of electricity to the US and it is anticipated these exports could be affected by power demands of future Canadian data centers. The functional unit is to provide electricity each year from 2015 to 2030 to the additional data centers, as defined in each prospective scenario (Fig. 1).

Inventory of elementary flows

To compute the inventory of elementary flows corresponding to the functional unit, it is necessary to identify the electric sources that are expected to power the extra data centers in each scenario. As previously stated, electric networks are complex systems in constant evolution and their modeling in LCA is problematic (Astudillo et al. 2015; Lund et al. 2010; Messagie et al. 2014; Roux et al. 2016; Soimakallio et al. 2011; Weber et al. 2009, 2010). Determining the electricity sources affected by changes in electricity demand remains challenging in C-LCA due to the uncertainty of the C-LCA approach (Mathiesen et al. 2009). Indeed, the identification of the affected technologies in C-LCA is usually based on current supply and demand elasticities and market trends. However, the identification process is uncertain because it can hardly capture the complexity of the real markets or the sudden changes they may face in the future. Moreover, the uncertainty of the identification process is greater when the temporal horizon of the study increases. An alternative approach to C-LCA is to model market effects with equilibrium economic models (Ekvall 2002). This approach has been adopted to study several topics: agriculture affected by biofuel demand (Kloverpris 2008; Kloverpris et al. 2010; Rajagopal 2014), forestry affected by bioenergy demand (Earles et al. 2013) or energy generation under different scenarios (Igos et al. 2015; Pietrapertosa et al. 2009; Eriksson et al. 2007). While it is possible to make raw assumptions about the future of Canadian electricity generation over 2015–2030, these assumptions would lead to uncertain results and hardly allow for the identification of specific power sources in each Canadian data center deployment scenario. An economic model was therefore preferred, the details of which are presented here.

Energy 2020

Energy 2020 energy model (Systematic Solutions 2014) was chosen because it appears especially promising for a Canadian study. Details about the model are provided in supplementary material.

The evolution of the global economy and demographics in 2015–2030 as well as the 2013 energy policies and climate change mitigation plan are considered in Energy 2020 simulations through the use of a prospective scenario (the BAU scenario mentioned in the previous section) that includes assumptions on future economy. These assumptions are presented in table S1 in supplementary material. This BAU scenario already considers the evolution of the Canadian ICT sector. Therefore, the five data center deployment scenarios described in the previous section represent power demands that are independent and additional to the BAU scenario. The data centers are assumed to be entirely powered by the electric grid.

To implement the additional power demand associated with the new data centers in each scenario, the *capital energy requirement* variable of the *data processing, hosting and related services* economic sector was adjusted exogenously in Energy 2020. The exogenous power demands of the data centers in each scenario are provided in table S2 in supplementary material. Six simulations were conducted: one for the BAU scenario and five for the case study scenarios.

The outputs of each simulation are the quantities of energy generated each year in each region by each energy source (aggregated by technology). These outputs are reproduced in table S3 in supplementary material. The electric sources affected by data center deployment in each scenario were then evaluated by comparing the simulation results of each scenario with the simulation results of the BAU scenario. Given that economic and demographic growths are already accounted for in all scenarios, this approach makes it possible to isolate the impacts of the data centers on the electric sources. The amounts of electricity generated by each technology affected by data center deployment (i.e. the marginal electricity) in each scenario are presented in table S4 in supplementary material.

Mapping ecoinvent with Energy 2020

The affected technologies identified by Energy 2020 were modeled with the ecoinvent database (version 3.2, (Weidema et al. 2013)) and Simapro (version 8.2.0.0, https://simapro.com). The list of ecoinvent processes used to model electricity generation is presented in table S5 in supplementary material. The model version of Energy2020 used in this study has seven technologies (biomass, coal, heavy fuel oil, diesel & gasoline, hydro, natural gas and other). When several ecoinvent processes corresponded to a single technology of Energy2020, a weighted average process was developed (based on ecoinvent data) on the basis of the regional electricity generated by each ecoinvent process (see fraction column in table S5).

Energy2020 and ecoinvent model Canadian electric technologies at the provincial level. Thus, the ecoinvent processes were used directly for Canada. For the US, ecoinvent provides datasets of networks regulated by the North American Electric Reliability Corporation (NERC). These networks are however aggregated in Energy2020 (in the model version used in this study). Consequently, seven weighted average US processes corresponding to the Energy2020 technologies were developed from the ecoinvent datasets. The weighting was made on the basis of the amount of electricity generated (based on ecoinvent data) by each technology in each NERC region (excluding Hawaii and Alaska networks).

Technology innovation

Modeling of technology innovation is described in supplementary material.

Environmental impact assessment

The environmental impacts were computed using Simapro and the IMPACT2002+ method (Jolliet et al. 2003) based on the amounts of electricity generated by each affected technology identified by Energy 2020 in the five scenarios (see table S4 in supplementary material). In this article, only the endpoint indicators are presented in the results section: *human health* expressed in disability-adjusted life years (DALY), *ecosystems* expressed in potentially disappeared fraction species.square meter.year (PDF.m^2.yr), *resources* in mega joules of primary energy needed to extract future resources (MJ primary) and *climate change* in kilograms of CO_2 equivalent (kg CO_2-eq).

Results

Figure 2 shows the annual GHG emissions related to marginal electricity consumed by additional Canadian data centers. As expected, the larger the number of new data centers, the higher the GHG emissions since more electricity is consumed. The trend is also observed for the other impact categories: human health, ecosystems and natural resource depletion.

<Figure 2>

Figure 2: Greenhouse gas emissions per year and per scenario as compared to the BAU scenario

A comparison of the scenarios based on the average impacts per marginal kWh of electricity consumed by data centers in 2015–2030 is illustrated in figure 3. Since the impact categories use different units, the results are expressed as percentages in order to be included in the same figure. In an impact category, one hundred percent is attributed to the scenario with the greatest impact for the category. Thus, the comparison of the impacts between scenarios is relative. Absolute numbers for each impact category are provided in table 1.

<Figure 3>

Figure 3: Relative impacts per marginal kWh, per scenario and per impact category

Table 1: Environmental impacts per marginal kWh, per scenario and per impact category

	Climate change	**Human health**	**Ecosystem**	**Natural resource**
	kg CO_2-eq/kWh	**10^{-6} DALY/kWh**	**PDF.m^2.yr/kWh**	**MJ primary/kWh**
Sc1 - BAU	0.93	2.09	0.120	12.1
Sc2 - BAU	0.90	1.92	0.105	12.1
Sc3 - BAU	0.91	1.87	0.094	12.3
Sc4 - BAU	0.90	1.83	0.095	12.2
Sc5 - BAU	0.85	1.69	0.105	11.6

Figure 3 shows that the impacts on climate change and human health per marginal kWh decrease when data center deployment increases. This trend is also observed for the ecosystem and resource indicators when scenario 1 is compared to scenario 5 but:

- Scenarios 4 and 5 have more impacts per marginal kWh on the ecosystem indicator than scenario 3;
- Scenarios 2, 3 and 4 have a little more impacts per marginal kWh on the resource indicator than scenario 1.

In other words, the impacts per MW of data center installed tend to decrease when data center deployment rises. This result is explained by the changes in the relative contribution of the marginal technologies used to generate electricity for the additional data centers (see Figure 4).

<Figure 4>

Figure 4: Relative contribution of marginal sources of electricity by scenario (2015–2030)

In Figure 4, it appears that natural gas and coal are the main marginal sources of electricity. The data centers deployed in the scenarios are therefore expected to be powered by these two sources in particular, whereas wind or biomass contribute very little to the data centers needs. It should be noted that marginal sources of electricity differ significantly from current sources of electricity in Canada: hydro (60%), nuclear (15%), natural gas (11%) and coal (10%) (International Energy Agency 2012). Consequently, the marginal GHG emissions intensities in table 1 are high (0.89-1.01 kg CO_2-eq/kWh) as compared to the Canadian emissions intensity for electricity (0.16 kg CO_2-eq/kWh in 2013 according to Environment Canada (2015)). The marginal electricity mix is the result of different trends :

1. Hydro dams and nuclear power plants have high building costs, which are hardly justified by the small power demand of the additional data centers (considering total Canadian

power demand). Moreover, these power plants take time to build. Therefore, in Energy 2020, natural gas thermal power plants are mostly built to provide extra electricity to Canadian data centers (Canadian policies discourage building coal power plants);

2. A large part of the electricity (60 to 70% depending on the scenario; percentages decrease with data center deployment) used to power the additional data centers is not produced in new power plants in Canada but rather sourced from existing power plants by reducing electricity exports to the US. Therefore, the US must compensate for this reduction in its supply sources. Energy 2020 models the compensation as mainly the construction of new natural gas and coal thermal power plants in the US (see marginal electricity by source aggregated over 2015–2030 in Figure 5).

<Figure 5>

Figure 5: Marginal sources of electricity by region (2015–2030)

Results also demonstrate that contribution of natural gas to marginal electricity sources increases (from 0.47% in scenario 1 to 0.53% in scenario 5) while the relative contribution of coal decreases (from 0.48% in scenario 1 to 0.38% in scenario 5) when data center power demand rises. The reduction in the natural gas contribution in scenario 5 (0.53%), as compared to scenario 3 (0.54%) and 4 (0.55%) is due to the increase in hydropower in Quebec (after 2020). This result typically reflects the non-linearity of the energy system's response to an increase in the power demand of Canadian data centers.

In terms of the environmental impacts, replacing coal with natural gas in marginal electricity generation to meet an increase in data center power demand results in a decrease in human health, climate change and ecosystems impacts per kWh since coal power plants have a worse score than natural gas power plants for these environmental indicators. Effect on resource is less noticeable since coal and natural gas power plants have similar scores for this indicator. The increase in bioenergy use explains the impact rise on ecosystem in figure 3 (see scenario 4 and 5). In ecoinvent, bioenergy implies the release in the environment of ashes containing metals which leads to significant impacts on ecosystem. Still, the greater contribution of hydro power when data centers are more broadly deployed in scenario 5 curbs the impacts per kWh for three of the four indicators.

Discussion

Evaluation of data center deployment scenarios

Scenario 5 generates greater direct environmental impacts than the other scenarios (cf. figure 2) but at the same time, it causes less impacts on all environmental indicators when it is compared to other scenarios on the basis of 1 MW of data center installed (cf. figure 3). It should be noted however that “climate change” and “resources” indicators are interlinked since fossil fuels contribute greatly to both of these indicators. Therefore, the environmental efficiency of scenario 5 is higher (when it is compared to other scenarios). Nevertheless, the complete evaluation of each scenario should involve the services provided by the data centers: improvement, substitution and rebound effects among human activities should be taken into account. While these effects are out of the scope of this study they may be important. Indeed, the deployment of new data centers can be expected to improve the penetration of ICT in society, thus allowing avoidance of more GHG emissions in the future (Global e-Sustainability Initiative and The Boston Consuting Group 2012; International Energy Agency 2014). In this situation, the GHG emissions of each scenario would be reduced, possibly leading to negative scores if emissions reductions in other sectors surpass the data center emissions. Moreover, the heat released into the atmosphere by the data centers may be significant but was not considered in this study due to the limited scope. Nevertheless, heat recovery for other activities, such as cultivation in greenhouses, could avoid the combustion of fossil fuels to generate heat. Considering such effects would result in more environmental benefits.

Still, several authors have pointed out that the ICT technologies might not reduce environmental impacts as compared to regular technologies. Ong et al. (2014) and Borggren et al. (2013) compared face-to-face meetings with videoconference meetings and concluded that the latter are not always better than the former. Additionally, several authors investigated the unwanted effects of ICT usage that can equal or even offset the positive effects expected by improving human activities with ICT (Takahashi et al. 2006; Ahmadi Achachlouei and Hilty 2016; Börjesson Rivera et al. 2014). If such unwanted effects were to occur, the impacts of each scenario would be more significant. Finally, the method presented in this study addresses the use phase of future data centers, but the other life cycle phases, such as the manufacture and end of life, should also be considered in the evaluation of data center deployment.

Impact of electricity generation

Electricity is often an important parameter in LCA (Lund et al. 2010). It is especially the case for data centers and ICT (Arushanyan et al. 2014). In this study it is observed that the impacts per kWh of data center usage over 2015-2030 highly depend on the modeling of the electricity mix. Indeed, while we conducted a consequential prospective LCA on the North American electric mix, other approaches would lead to different results and conclusions. These approaches, based on the Energy 2020 results, are described hereafter and their results are presented in table 2:

- In the *2015 (Canada)* approach the impacts are computed using the 2015 Canadian electric grid mix, assuming the grid mix will remain unchanged up to 2030;

- The *2015 (US+Canada)* approach is identical excepted that the US and Canadian electric mixes are both considered;
- In the *BAU 2015-2030 (Canada)* approach the impacts are computed using the business as usual evolution of the Canadian grid mix up to 2030;
- The *BAU 2015-2030 (US+Canada)* approach is identical except that the US and Canadian electric mixes are both considered;
- In the *Marginal 2015-2030 (Canada)* approach, the impacts are computed using the marginal Canadian grid mix for the scenario 5.
- *Marginal 2015-2030 (US+Canada)* approach, the impacts are computed using the marginal US and Canadian grid mix for the scenario 5.

Table 2: Environmental impact per kWh

Model for 1 kWh	kg CO_2-eq/kWh	10^{-7} DALY/kWh	10^{-2} PDF.m^2.yr/kWh	MJ primary/kWh
2015 (Canada)	0.16	0.7	2.6	4.9
2015 (US+Canada)	0.60	15.5	7.8	10.1
BAU 2015–2030 (Canada)	0.16	0.7	2.7	4.7
BAU 2015–2030 (US+Canada)	0.63	16.0	8.1	10.3
Marginal 2015–2030 (Canada)	0.57	2.1	10.3	8.8
Marginal 2015–2030 (US+Canada)	0.85	16.9	10.5	10.4

Table 2 indicates that the environmental impacts per kWh largely differ depending on the approach followed to compute the electric grid. In this study, the parameter affecting the most the impact per kWh is the spatial border of the system (inclusion or not of USA).Then comes the choice of the attributional or consequential approach (BAU or marginal), which has a lower but still significant influence on the impact per kWh. Finally, the temporal horizon has less influence in the case of the attributional LCA approach (not computed in the case of the consequential LCA approach).

Choosing the right approach to compute the electric grid mix for a study depends on the objective of the study. In our study, the objective is to evaluate the consequences of building more data centers in Canada as compared to a BAU scenario. Since the Canadian electricity exports to US are found to be affected by the data center deployment, the US grid mix should also be included in the computing of the electric grid mix. Therefore, the "Marginal 2015–2030 (US+Canada)" approach of table 2 should be used.

If the objective was to evaluate the carbon footprint of additional data centers, then the 2015–2030 emissions computed in a relevant data center deployment scenario for US and Canada should be used. The use of the BAU 2015-2030 (US+Canada) approach would also be suitable if the data center power demand would remain low in comparison to the total power generation of US and Canada. In this case, the use of the marginal factors would not be fair since certain low-emissions technologies such as nuclear would be excluded from the marginal electricity. Anyway, current legislation and guidelines for carbon footprint assessment do not consider marginal electricity and the debate on marginal electricity allocation is unresolved.

The 2015–2030 (BAU, Canada) approach should not be used since it would not capture the US side-effect. Such factors would largely underestimate the impacts of the Canadian data centers. However, in the context of a tax on environmental externalities, the attribution of the US environmental burden to the Canadian users is debatable and could justify the use of the 2015–2030 (BAU, Canada) approach. Nevertheless, the question of the attribution of the indirect effects of decision-making has not yet been answered in the context of ecological footprints.

2015 impacts factors (Canada or US + Canada) should not be used to study future emissions of data centers since they do not reflect the future evolution of electricity generation. To summarize, the choice of the approach should be in agreement with the geographical and temporal scopes of the study and cover anticipated indirect effects. Marginal approaches are especially relevant in the context of optimization because they reflect the non-linearity of impacts. However, the use of marginal approaches results in attribution of different impacts between marginal and non-marginal users. Nevertheless, such equity problem can be overcome by combining attributional and marginal approach to share the marginal impacts among all users.

Contributions to Energy 2020 and LCA

Combining Energy 2020 and LCA enhances both tools. On one hand, the approach adds environmental indicators based on the power plants' life cycles to the Energy 2020 results, providing more valuable information on the potential environmental impacts of future energy policies since more environmental indicators are considered. On the other hand, Energy 2020 makes it possible to conduct an LCA using prospective (Pesonen et al. 2000) and consequential (Ekvall and Weidema 2004) methodologies in the context of the North American energy sector. Instead of using expert judgments, extrapolating time series, making uncertain assumptions and using simplified economic models as in standard prospective and consequential LCA, an acknowledged advanced model is used. Therefore, it is expected that the proposed method will provide more robust results for LCA involving the future evolution of the North American energy sector. But the use of economic models in LCA is quite new (Kloverpris 2008; Earles 2011; Dandres et al. 2011) and further studies are required to illustrate the advantages and flaws of the combination.

Limitations, uncertainty and recommendations

Energy 2020 is expected to be one of the best energy models to investigate changes in the North American energy sector. However, it relies on assumptions about the future evolution of macroeconomic variables and economic modeling, which cannot predict non-economic events such as war, natural disasters, economic crisis or a political decision. For instance, this project was achieved in 2014 at a time the US clean power plan was not announced. Thus, our simulations do not take into account the future reduction of carbon intensity in US electricity generation as targeted by the US clean power plan and our results probably overestimate the marginal emissions from US power plants. Additionally, there is some uncertainty on the electric mixes due to imperfect convergence of solutions computed by the Energy2020 (see Tables S2 and S4 in supplementary material). Therefore, the results of the model should not be taken as-is but rather used to identify key trends and unwanted effects. In this case study, the main result may be the unexpected reduction in Canadian electricity exports to the US and the related negative environmental effect. By being aware of the unwanted effect before it occurs, it is possible to anticipate and take appropriate measures (e.g. subsidize the generation of renewable energy to power data centers in Canada) to counter it. An iterative approach would support the design of an optimal strategy.

Regarding LCA, the limitations pertain to the quality of data used to model electricity generation and evaluate the environmental impacts. Indeed, generic processes were used to model power plants regardless of the power plants specificities. Thus, there is uncertainty with regards to the computed emissions. Moreover, technological changes are imperfectly modeled in this LCA. While future technologies are expected to be more efficient than current ones, data collected on power plants efficiency suggests thermal technologies are not improved. Therefore, the results may overestimate the future impacts on the environment since natural gas and coal technologies are found to play a major role in the future. Prospective data cannot be obtained by measurement and must be forecasted. However, forecasting requires significant resources (e.g. a panel of experts (Godet et al. 2004)) that were not available at the time of the study. Also, environmental impacts were computed regardless of the geographic location of the emissions even though the site of an emission may affect its fate in the environment and result in different environmental impacts depending on the location (Manneh et al. 2010). While, ideally, the location of the emissions should be taken into account, the regional impact assessment models in LCA are still under development. Also, it was assumed the cause and effects chains that link the substances emissions to the environmental impacts would remain stable in the future. However, this assumption may overestimate the capacity of ecosystems to resist to damages and fail to represent the cases were this capacity is exceeded. Such situation could occur, for instance, in the case of acidification (Roy et al. 2012). Finally, due to technical issues and lack of resources, it was not possible to investigate a large number of scenarios, conduct sensitivity analyses or run Monte Carlo simulations to evaluate the uncertainty of the final results. Indeed, such analyses are time- and resource-consuming when an equilibrium model such as Energy 2020 in used sequentially with LCA (Dandres et al. 2014a). Moreover, the evaluation of impact assessment uncertainty is not currently possible in Simapro due to lack of data.

Conclusion

The environmental assessments of data centers and ICT are closely linked to electricity generation modeling. The accuracy of electricity impact data is a crucial parameter in environmental ICT studies. Therefore, it is relevant to study the future electric grid mixes that will supply future ICT systems in order to evaluate their environmental performances. Since electric grid mixes evolve in time, adequate tools must be used to model them properly rather than applying *ceteris paribus* or business as usual assumptions. In this study, a regional economic model (Energy 2020) was used to represent the changes in energy generation in Canada and the US in 2015–2030. Combined with the LCA methodology, the model made it possible to evaluate the environmental impacts of several data center deployment scenarios in Canada and determine those that generate the least impacts per MW of data center built. In this case study, the largest deployment of data centers (+ 750 MW) is the most efficient scenario for three of the four environmental indicators. A smaller deployment of data centers (+150 MW) would minimize the impact per MW of data center built on ecosystem but would not minimize impacts on the human health and climate change indicators. Moreover it would maximize the impact on the resource indicator.

The combination of a techno-economic model and LCA methodology capitalizes on the use of both tools: the model provides prospective scenarios and LCA computes several environmental impacts based on the technologies' life cycles. While the proposed methodology has been applied to elucidate the consequences of data centers deployment, it could also be use to evaluate changes in other industrial activities. A significant result is that the increase in the power demand of the Canadian data centers causes a reduction in electricity exports to the US. Consequently, US electricity generation must increase to compensate for the lack of electricity in the US. Since this compensation is achieved with coal and natural gas, major environmental impacts are indirectly generated by the deployment of Canadian data centers. However, the Clean Power Plan announced in August 2015 (after the study achievement) is expected to reduce the contribution from fossil fuels in US electricity generation. Therefore, marginal impacts from US might be smaller than those anticipated in this study. Moreover, whether these indirect impacts should be attributed to the Canadian data centers is debatable. Indeed, while there is a causal link between the increase in Canadian data center deployment and the decrease in electricity exports to US, Canadian electricity providers have no control over the choice of the fuel for the US electricity generation. This issue is of major concern in terms of GHG emissions since the climate change issue is a global one. Therefore, guidelines must be established in order to contend with indirect effects in carbon footprint methodologies.

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